Characterization of Proton Damage in Light-Emitting Diodes†

A. H. Johnston and T. F. Miyahira
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

I. Introduction

Displacement damage in light-emitting diodes is an important issue for space applications [1-6]. Some LEDs are highly susceptible to displacement damage, making them among the most sensitive components with severe degradation at very low radiation levels in environments dominated by protons. Although other types of LEDs are far less affected by displacement damage, the harder device technologies have much lower initial light output than the softer LED types. Selection of LED technologies for space is a complex issue, requiring tradeoffs of several different factors.

Damage in some types of LEDs is affected by injection conditions during and after irradiation [1-5]. This adds a further level of complexity to radiation characterization because measuring the device at high currents during a sequence of irradiation-and-measurement steps will inadvertently cause some of the damage to recover, invalidating the radiation characterization for applications where the device is operated infrequently or operated at low currents. Such conditions are frequently encountered in many system applications, as well as in optocouplers (which contain LEDs) [7-9]. Investigation of injection-enhanced annealing is one of the main objectives of the present paper.

Another important factor is degradation during normal operation (wearout) which causes gradual decrease in light output [10]. Wearout degradation produces changes in LED characteristics that have many similarities to displacement damage. One question that needs to be answered is whether wearout degradation can be added independently to radiation damage, or whether it reduces or increases the sensitivity of LEDs to radiation.

II. Experimental Approach

Devices were selected from several commercial suppliers, including Optodiode, Optek, Hewlett-Packard and Hamamatsu. They included amphoterically doped and double-heterojunction devices in the 660 to 950 nm range that are compatible with silicon detectors, and one 1300 nm device. Properties of the device types used in the study are shown in Table 1; more complete information about fabrication technology (including amphoteric doping) will be provided in the complete paper.

Table 1. Devices Selected for the LED Study

Type	$\lambda(\mu m)$	Manufact.	Technology
L3882	660	Hamamatsu	Diffused
OD800	810	Optodiode	Double-heterojunction
L7558	830	Hamamatsu	Double-heterojunction
L3989	850	Hamamatsu	Double-heterojunction
OP233	870	Optek	Amphoteric
OD880	880	Optodiode	Amphoteric
OP130	930	Optek	Amphoteric
LST0400	1300	H-P	Double-heterojunction

All irradiations were done at the University of California Davis cyclotron using 50-MeV protons.†† Samples were mounted on special circuit boards that allowed irradiation of groups of 12 parts. Devices were measured before and after each irradiation using a Keithley 230 current source and a Hewlett-Packard data sequencer. Light output was measured with a silicon phototransistor, connected as diode, with a Keithley 617 electrometer.

Special measurements, including post-radiation annealing measurements, were made using a Hewlett-Packard 4156 parameter analyzer, along with a photodiode to monitor light output.

III. Degradation of Various LED Types

A. Parameter Degradation

For many LEDs, light output is the critical parameter to characterize degradation. This approach has been used in the past to measure LEDs and optocouplers, usually normalizing the results to pre-irradiation values. Such degradation is easily interpreted, and allows unit-to-unit variability to be easily incorporated. Figure 1 shows the typical degradation of four types of LEDs normalized to initial light intensity. Note that amphoterically doped devices are damaged significantly at far lower radiation levels. Damage in the amphoterically doped devices also depends on bias conditions during irradiation because of injection-dependent annealing (see Section IV). In contrast, damage in the double-heterojunction devices that we have studied is unaffected by bias conditions during or after irradiation.

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††Proton damage depends on energy. There is some disagreement between theoretical calculations [11] and experimental results at high energies [12], but the energy dependence agrees up to 50 MeV, which is also near the mean energy of many spectra in Earth orbiting systems.

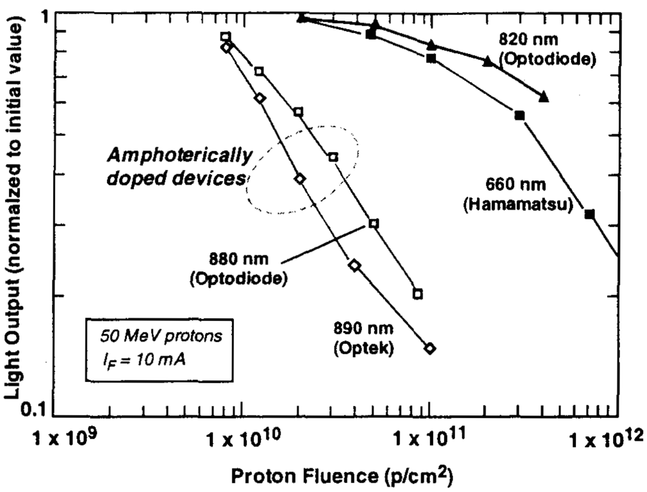

Figure 1. Degradation of four types of LEDs at moderate current levels.

Although degradation of light output is always of importance, some types of LEDs exhibit large increases in recombination current at low injection after irradiation, and that type of degradation can be more important than degradation of light output in some cases [5]. That topic will be addressed in the full paper.

B. Diffusion-Limited Parameter

The dependence of LED degradation on fluence is more complex than for conventional components (such as discrete transistors). At low currents surface recombination within the LED is important, and non-radiative recombination often dominates device behavior. At moderate currents, above the threshold region, light output is approximately proportional to forward current through the LED.

Rose and Barnes [2] showed that damage could be related to lifetime by a power law using the equation

$$\Gamma = [(I_0/I)^n - 1] = \tau_0 K \Phi \qquad (1)$$

where I_0 is the pre-irradiation light intensity, I is the (reduced) intensity after irradiation, n is an exponent between 0 and 1, τ_0 is the initial minority carrier lifetime, K is the damage constant, and Φ is the proton fluence. Note that K depends on proton energy [ref] and injection level. They used the product $[\tau_0 K]$ to compare radiation sensitivity of different LED types.

Rose and Barnes demonstrated that for constant LED current the exponent n = 2/3 for the case where both forward current and light output are dominated by diffusion, and that n = 1/3 for the case where forward current is controlled by space-charge recombination, but the light output is controlled by diffusion. Thus, in the case where diffusion dominates both processes the parameter Γ should be linear with fluence for n = 2/3.

This is a useful way to examine LED data, although it is less straightforward than simply plotting normalized optical power output I/I_0 (as in Figure 1).

Degradation of a typical amphoterically doped device using Equation 1 is shown in Figure 2. Two sets of curves are plotted: one using am exponent of one, the other with the 2/3 value predicted theoretically for an LED operating in a diffusion-limited mode. The slope is almost exactly 1 in the latter case, although there is a slight departure at low fluences. This change in slope at low fluences was observed for four different types of amphoterically doped LEDs, obtained from three different vendors, and appears to be a general characteristic of damage in those structures.

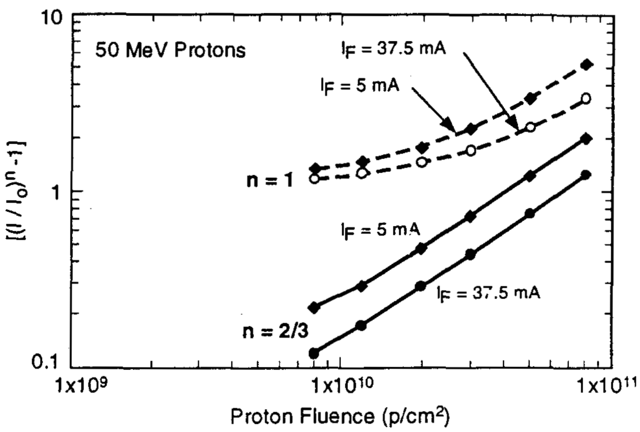

Figure 2. Damage factor for a typical amphoterically doped LED using the power-law relationship of Equation 1.

Damage in the double-heterojuction devices was not as well described by Equation 1. Figure 4 shows damage in a representative double-heterojunction LED using two different exponents. The damage was linear, assuming n = 2/3 in Eq. 1, but the slope was less than one (approximately 0.8). The slope is further reduced at high fluences, probably because of carrier removal, which is not considered in Equation 1.

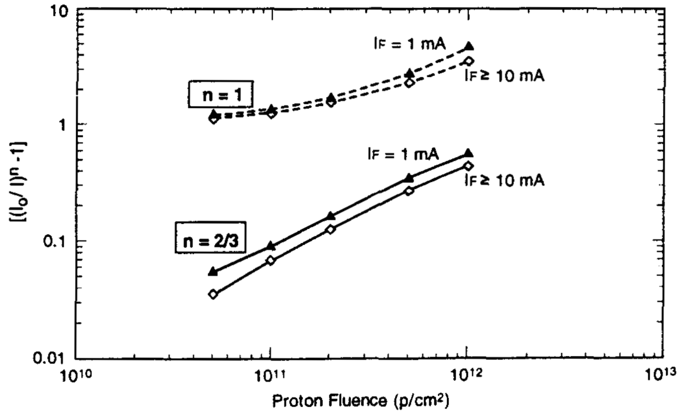

Figure 3. Damage factor for a typical double-heterojunction LED using the power law relationship of Equation 1.

Damage linearity of the other LED types will be discussed in the full paper.

IV. Annealing Studies

Last year we compared injection-dependent annealing in three types of amphoterically doped LEDs and noted that the annealing under different injection conditions could be normalized to the total injected charge that passed through the device after irradiation [5]. However, those tests were done after all devices had been irradiated to 8 x 10^{10} p/cm^2 and were done over a limited time period. The present study investigates the dependence of annealing on fluence, and also examines annealing from the standpoint of the damage parameter Γ (see Equation 1), as well as extending the annealing time interval.

Figure 4 shows how the light output of a typical OD233 LED recovers with time when it is continuously biased with a forward current of 5 mA after the irradiation is stopped (devices were irradiated without bias). The damage is stable after irradiation, and only recovers during time periods when the device is forward biased. A significant amount of the damage recovers, both at low and high fluences.

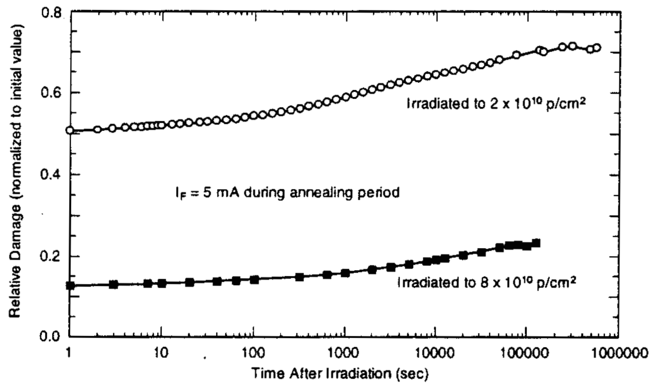

Figure 4. Recovery of light output after irradiation for LXX amphoterically doped LED.

A different way to examine this data is to note first that the recovery depends on the total charge, and that the relative damage is more accurately described using the parameter Γ in Equation . The data in Figure 4 is plotted in this manner in Figure 5.

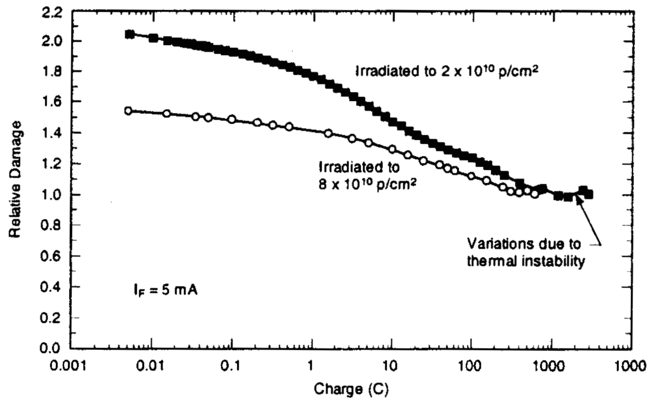

Figure 5: Results of Figure 5 plotted to reflect the damage factor and charge dependence.

Note that more of the damage actually recovers at low fluence compared to higher fluences. All of the amphoterically doped devices exhibited annealing with similar relationships. The amount of charge for 50% recovery was between 3 and 8 coulombs for all four amphoterically doped device types. Injection-dependent annealing was also observed for the Hamamatsu L3882 device (660 nm, diffused technology). Further details will be provided in the complete paper. None of the double-heterojunction technology devices were susceptible to injection-enhanced annealing. The general shape of the annealing response A(Q) after charge Q in Figure 5 can be described by the equation

$$\Gamma(Q) = (\Gamma_o - \Gamma_f) / (1 + Q/Q_f) + \Gamma_f \qquad (2)$$

where Γ_o is the initial value of damage at short time (zero charge), Γ_f is the final damage value at infinite charge, and Q_f is the charge for which the recovery saturates. This equation allows the effects of annealing to be calculated for arbitrary time and current values. Further details will be provided in the full paper.

V. Effects of Aging and Wearout

Unlike conventional semiconductors, III-V photonic devices exhibit continual degradation when they are operated over extended time periods [10]. GaAs and AlGaAs devices are particularly affected. One issue in applying LEDs in space is whether radiation degradation adds to the degradation that is expected from "wearout." Samples of three types of devices were operated for periods of more than one thousand hours at room temperature, which degraded their initial light output by 10 to 20%; the forward voltage also decreased slightly, just as for irradiated samples. Figure 7 shows the degradation of light output for typical "aged" devices, with 100 mA (maximum rated current) applied during aging, and measurement made at a forward current of 10 mA.

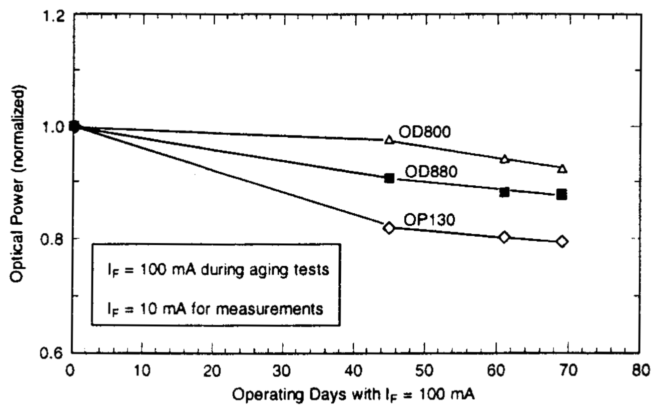

Figure 7. Degradation of various LED types after extended operation at maximum rated current.

Subsequent radiation tests were done on those devices to compare their response with that of devices from the same lot that had not been subjected to life testing. Degradation of the "aged" samples were indistinguishable from samples that had not been subjected to high currents prior to irradiation (details will be provided in the full paper, along with comparisons of the effect of aging at 50% of rated maximum current with the results in the summary for aging at 100% of rated current). The important point is that damage produced by aging appears to be independent of the damage produced by radiation, and thus must be added to radiation damage for applications that involve operation over extended time periods.

V. Discussion

Characterization of LED radiation degradation is more difficult than for conventional silicon-based electronic devices. Several factors need to be taken into account, as delineated below:

(1) Damage depends on current, and is generally less at high currents

(2) I-V characteristics change as well as light output

(3) Damage may partially recover due to injection-enhanced annealing

(4) The output is strongly temperature dependent, affecting measurement precision; temperature variability in the eventual application must also be considered in interpreting radiation degradation

(5) Some devices may degrade in an abnormal manner, with large increases in non-radiative current at moderate injection levels

(6) Degradation of light output during normal operation adds to radiation degradation and also leads to operation of devices at currents significantly lower than maximum rated values.

In addition to these factors, it is also necessary to consider the relative initial light output. For example, although amphoterically doped LEDs degrade more rapidly than other types of LEDs, their initial light output is much higher. The full paper will compare degradation of the different devices that takes aging and relative light output into account.

References

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